

PROJECT MANAGEMENT CHALLENGE 2007



SHARED VOYAGES: LESSONS LEARNED FROM THE EXTERNAL TANK

*How I Found Out That We Are
Not Nearly As Smart As We
Thought We Were*

“We don’t know a millionth of one percent about anything.”

Thomas A. Edison

“Progress comes from the intelligent use of experience.”

Elbert Hubbard

“Experience teaches the teachable.”

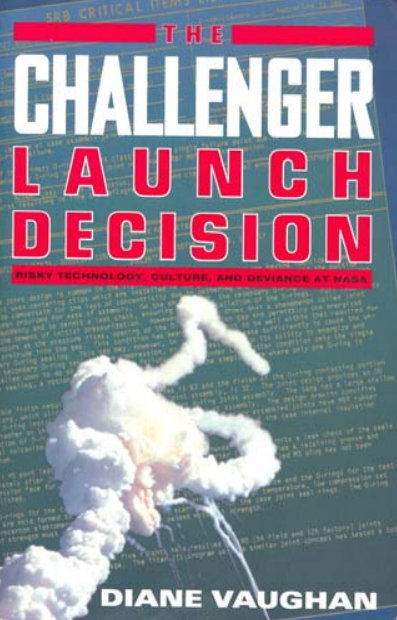
Aldous Huxley

‘It ain’t what ya don’t know that will get ya, it’s what you think ya know that ain’t so.’

Yogi Berra

“The ET is just a big, dumb drop tank.”

anonymous Shuttle Commander in the early years



Quotes from Chapter 6: *Engineering Culture*

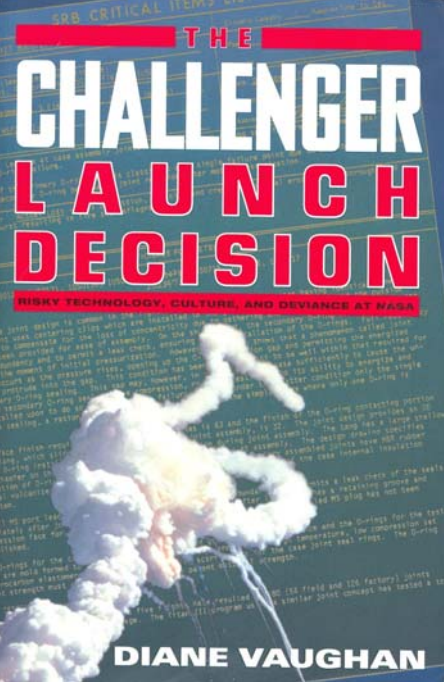
...the messy interior of engineering practice, which after the accident investigation looks like “an accident waiting to happen” is nothing more than “normal technology. Normal technology...is unruly.

...experts are operating with far greater levels of ambiguity, needing to make uncertain judgments in less than clearly structured situations.

Practices do not follow rules, rather, rules follow evolving practices.

In the implementation and operation of complex technological systems, new rules and relationships are continually being invented and negotiated.

Information generated by anomaly, by discrepancy between expected and actual outcomes becomes the means by which fallible rule sets are corrected and moved toward solution sets. This general tendency is profoundly realized in engineering work. Learning proceeds through iteration.



Quotes from Chapter 6: *Engineering Culture*

Absolute certainty can never be attained for many reasons, one of them being that even without limits on time and other resources, engineers can never be sure they have foreseen all possible contingencies, asked and answered every question, played out every scenario.

Many technologies...cannot be tested in laboratory conditions. Tests are conducted on models, which can only approximate the complex systemic forces of nature and technical environment. This situation creates risk: the world outside the laboratory becomes the setting for experiments.

Judgments are always made under conditions of imperfect knowledge.

The essence of engineering as a craft is to convert uncertainty to certainty, figuring probabilities and predictions for technologies that seldom stay the same...in the workplace, engineers formulate the rules as they go along, attempting to capture the unruly technology with numbers, experienced based theories, and practical rules.

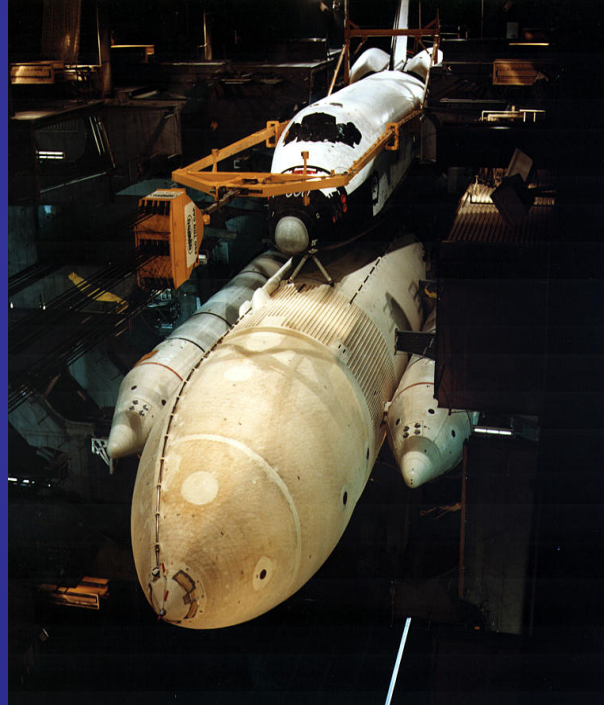
Even in closure there is ambiguity.

The four letter “F” Word

History of the External Tank



STS-1: DECEMBER 29, 1980



STS-2: COLUMBIA IS MATED TO
ITS ET/SRB STACK



REPAIR OPERATIONS to holes
caused by woodpeckers ON ET
FOR STS-70

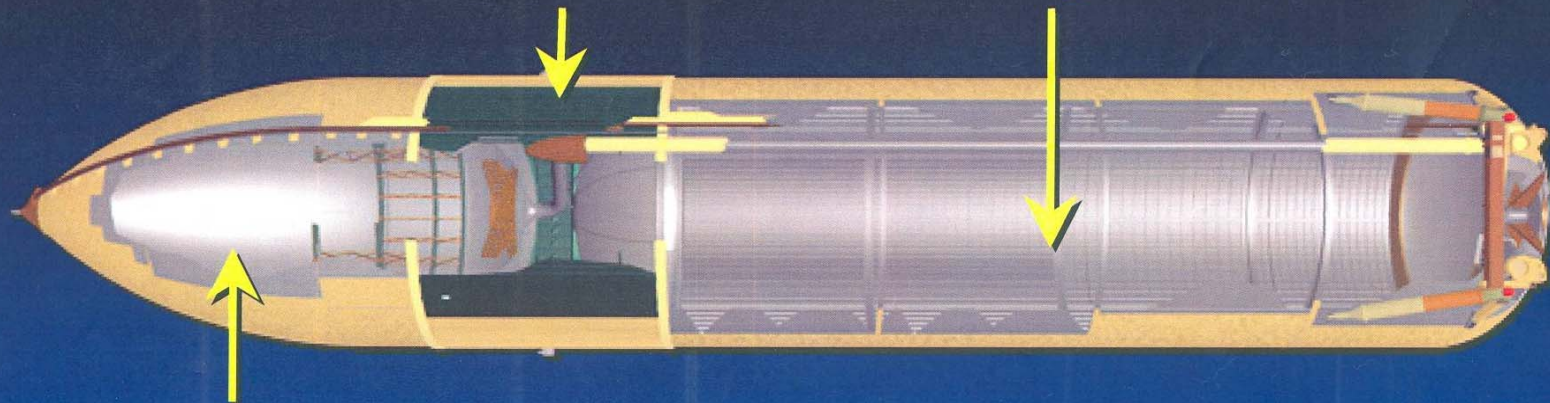
Only part of the Space Shuttle Vehicle not returned for reuse and evaluation!

Intertank

- Unpressurized Structure

Liquid Hydrogen Tank

- 231,000 lbs. / 309,139 gals. Fuel
- - 423 Degrees Fahrenheit



Liquid Oxygen Tank

- 1,385,000 lbs. / 145,138 gals. Oxidizer
- - 297 Degrees Fahrenheit

Length = 153.8 Feet; Diameter = 27.6 Feet

ET Production History

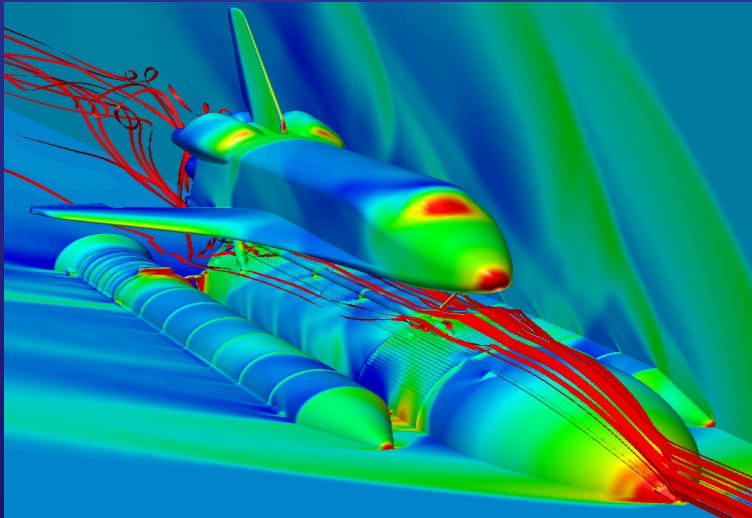
121 Units Delivered to Date
Three Versions:

	Delivered	Flown
Standard Weight Tank Al 2219 (Al=Aluminum) Dry Wt. 77,099 lbs. (actual ET1)	6	6 (1981 – 83)
Lightweight Tank Al 2219 Dry Wt. 65,767 lbs (actual ET71)	87	86 (1983 – 98, 2002, 2003)
Super Lightweight Tank Al 2195 (Al-Li = Aluminum Lithium) Dry Wt. 58,319 lbs. (actual ET96)	28	21 (1998 – Present)

Substantially Completed Tanks 4

External Tank Foam pre-STS-107

Prior to STS-107,
foam loss was regarded as a vehicle processing issue,
not a safety of flight issue.



ET CRYOINSULATION: General Properties

Foam / Property	(HCFC) NCFI 24-124 (CFC) CPR 488	(HCFC) NCFI 24-57 (CFC) NCFI 22-65	(HCFC) PDL 1034 (CFC) PDL 4034	(HCFC) BX265 (HCFC) SS 1171 (CFC) BX 250
(% of total foam)	(77%)	(7%)	(1%)	(14%)
Application	LH2,L02,I/T sidewall	LH2 aft dome	Closeouts and repairs	LH2 forward dome, L02 aft dome, closeouts
Process	Spray	Spray	Pour/Mold	Spray
Description	Isocyanurate	Isocyanurate	Urethane	Urethane

Requirements	Spec Req	Typ Prop	Flt Pred	Spec Req	Typ Prop	Flt Pred	Spec Req	Typ Prop	Flt Pred	Spec Rez	Typ Prop	Flt Pred
Density PCF	<u>2.0-2.5</u> 2.1-2.6	<u>2.2⁸</u> 2.4	Lighter ⁶	<u>2.6-3.1</u> 2.6-3.1	<u>2.97</u> 2.90	Heavier ⁶	<u>2.3-3.1**</u> 2.3-3.1	<u>3.3**</u> 2.6	same ⁶	<u>1.8-2.6</u> <u>1.8-2.6</u> 1.8-2.6	<u>2.4</u> <u>2.4</u> 2.4	same ⁶
Tensile RT (psi)	<u>30min</u> 35min	<u>44</u> 54	19	<u>40min</u> 40min	<u>66</u> 71	19	<u>60</u> 60	<u>113</u> 104	19	<u>35min</u> <u>35min</u> 35min	<u>80</u> <u>53</u> 75	19
Tensile -423° F (psi)	N/A ¹	<u>34</u> 41	19	N/A	<u>49</u> 47	19	N/A	<u>50</u> 49	19	N/A	<u>74</u> <u>62</u> 53	19
Tensile +300° F (psi)	N/A	<u>32</u> 37	19	N/A	<u>36</u> 45	19	N/A	<u>71²</u> 53	19	N/A	<u>53</u> <u>35⁵</u> 47	19
Compression (psi)	<u>25min</u> 24min	<u>33</u> 40	20	<u>35min</u> 35min	<u>49</u> 51	20	<u>30</u> 30	<u>61</u> 42	20	<u>24min</u> <u>24min</u> 24min	<u>43</u> <u>30</u> 42	20
Recession Rate @ 7 BTU/ft sq sec (in/sec)	N/A	<u>0.0094</u> 0.0168	lower ⁶	N/A	<u>0.0099⁷</u> 0.0099 ⁷	same ⁶	N/A	<u>0.0303</u> 0.0235	higher ⁶	N/A	<u>0.031</u> <u>0.017³</u> 0.024	lower ⁶
Thermal Cond @ R/T BTU/hr ft °F)	0.025	<u>0.017</u> 0.017	same ⁶	<u>0.0225</u> 0.0158	<u>0.0180</u> 0.0156	higher ⁶	<u>0.016</u> 0.016	<u>0.015</u> 0.012	higher ⁶	<u>0.015</u> 0.015	<u>0.015</u> <u>0.013</u> <u>0.011</u>	higher ⁶
Cryostrain (ksi)	61 @-423	<u>65 @-423</u> 65 @-423	pass	58 @-423	<u>65 @-423</u> 65 @-423	pass	N/A	<u>60 @-320</u> 60 @-320	pass	N/A	<u>65 @-423</u> 65 @-423	pass

¹N/A- Not Applicable

²+200°F Values

³@ 4 BTU/ft sq sec

⁴Max density 3.0 in dome area allowed

⁵@ + 200°F

⁶Means new vs. old

⁷Radiant heating

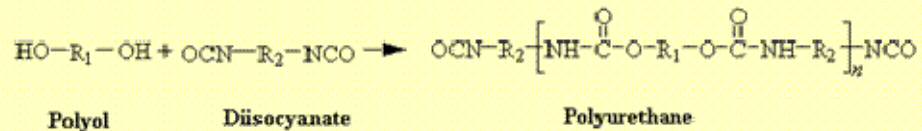
⁸2.4 – 2.8 PCF for thick/thin

^{**}Spec Req-cup pour; Typ Prop-dissection

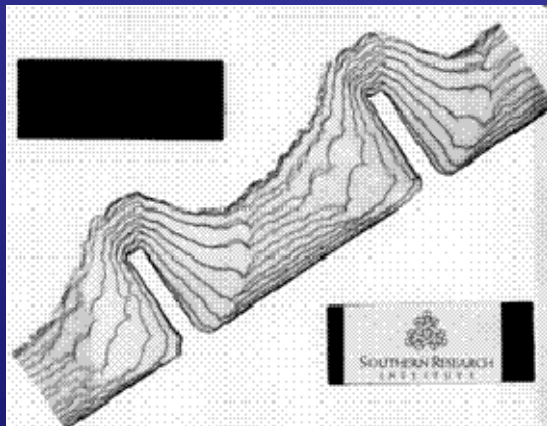
Reference: ET Project – Design Values for Non-Metallic Materials, LM 809-9600 Rev C, May 2006.

ET CRYOINSULATION: Key Material Engineering Aspects

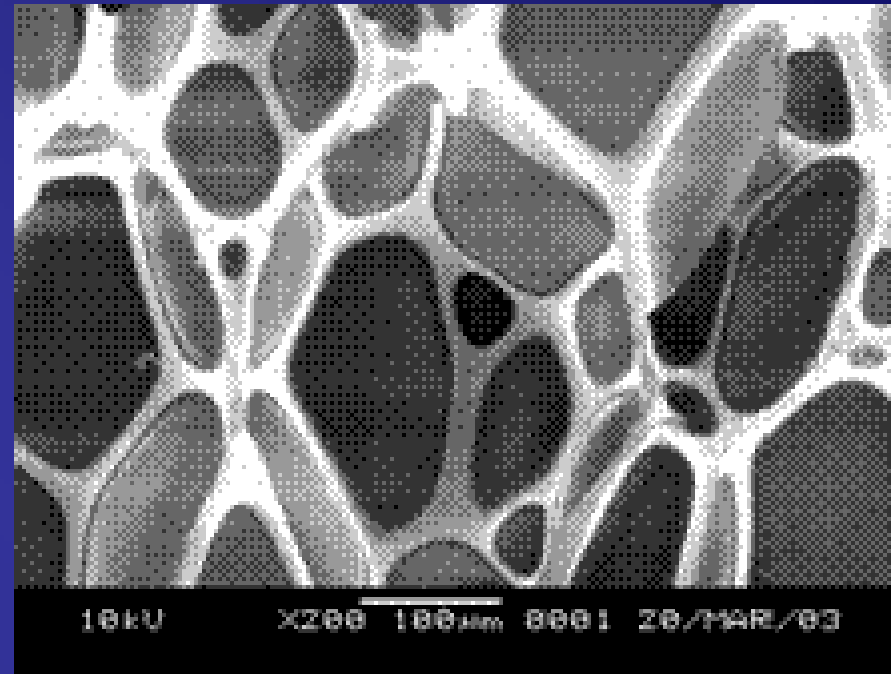
Levels of Structure



Polymeric Structure



Knitline Geometry
Substrate Geometry



Cellular Structure

Columbia (STS-107)



- In the early morning on Saturday, February 1, 2003, the Space Shuttle Columbia broke up during entry. All seven crew members were killed.
- 81 seconds after launch, foam insulation on the External Tank broke off and struck the Shuttle's wing at Mach 2.46, creating a hole roughly the size of a pizza box.
- When Columbia reentered the atmosphere to land, highly heated plasma entered the breached wing, and burned or melted away the wing's internal structure. The structural failure of the wing led to the loss of vehicle control and the vehicle broke apart as it descended toward Earth.





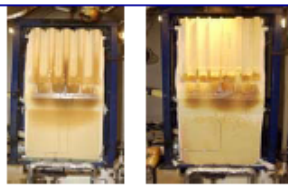

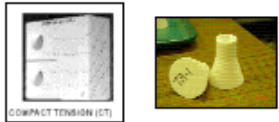

Crew of the Space Shuttle Columbia

CAIB: "Foam Did It!"

but WHY did the foam do it?

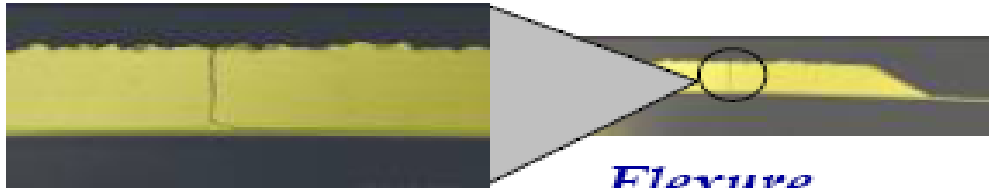
ET Foam Certification Testing

• Plans for Completion of Certification Tests

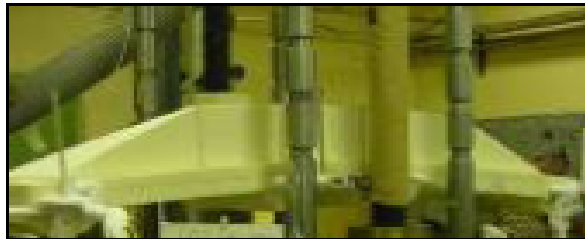
Test	Test Article	Status of Testing Required for FRR	Test Report Status (ECD)
809-9446, Wide Panel Testing of NCFI 24-124		✓	4/22/05
809-9538, Cryoflex Capability, PDL-1034 and PDL-1034 / BX-265 for LO2 Feedline Bellows Rainshield		✓	4/19/05
809-9630, Flaw Tolerance of Enhanced Flange Closeout		✓	4/23/05
809-9773, Thermal Vacuum Testing with Altered Density		✓	4/23/05
809-9772, Fracture Toughness: Phase II		4/19/05	4/23/05
809-9473, Impact Damage Tests and Assessment		✓	4/24/05

Remaining Certification Tests have been Identified, Scheduled and in Work to Support Return to Flight FRR

Loss of ET Thermal Protection System Acceptance Rationale



Flexure



PAL Ramp Capability

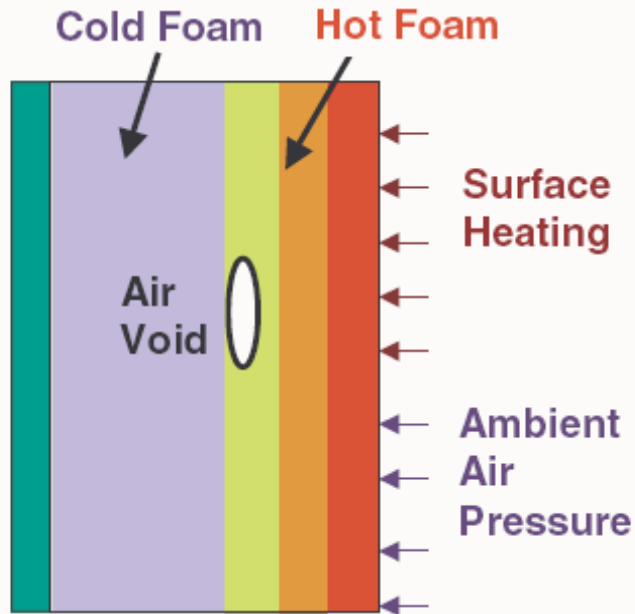


Cryoflex



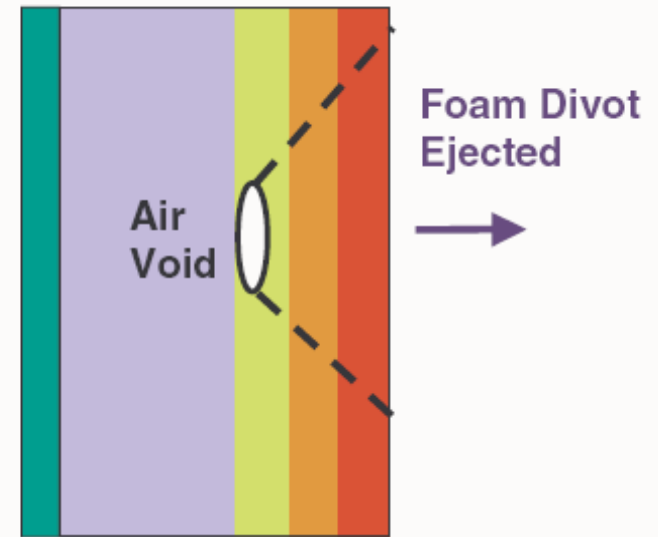
*System (Flange)
Thermal/Vac*

How Air-Divots Are Formed



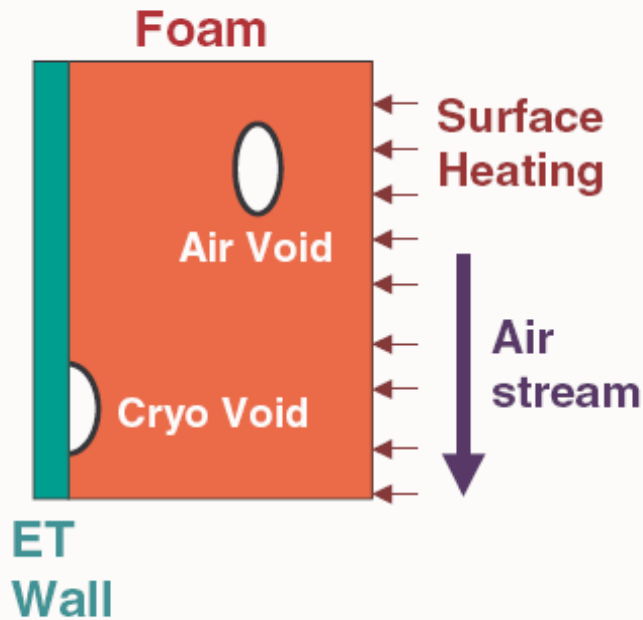
ET Wall

Step 1: During ascent of ET, heat penetrates into foam and ambient air pressure drops



Step 2: Physics code predicts when stresses in foam cause rupture and speed of divot is predicted using $F = ma$

Codes for Predicting Foam Debris



- **Foam Physics Model (Monte Carlo Runs)**

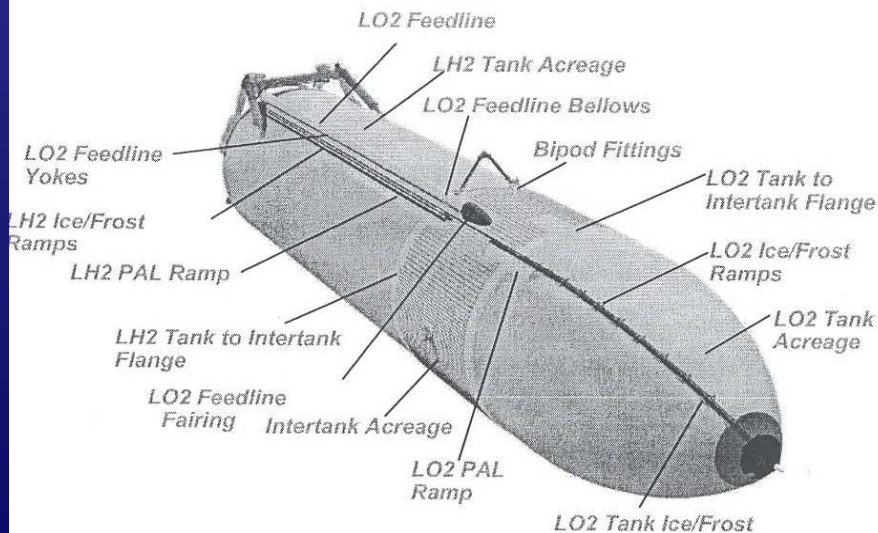
- Physics & engineering models for foam
- Inputs are statistical models for defects in foam
- Material properties of foam are also statistical
- Debris liberation predicted by fracture (LEFM)
- Debris Tables generated based on Monte Carlo runs for Shuttle ascent conditions and predictions for voids in foam

- **Multi-Physics Model (2-D Analysis)**

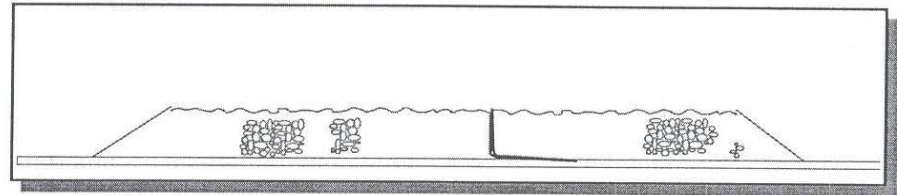
- Uses FEMLAB multi-physics code
- Models detailed foam physics e.g. complex stress states and thermal distributions
- Used for regions of ET that require special attention to detail: LH2 Flange (Intertank)
- Model predicts characteristics of foam divots: time-of-release, mass, and shape

Thermal Protection Verification (TPS) / Validation Issues

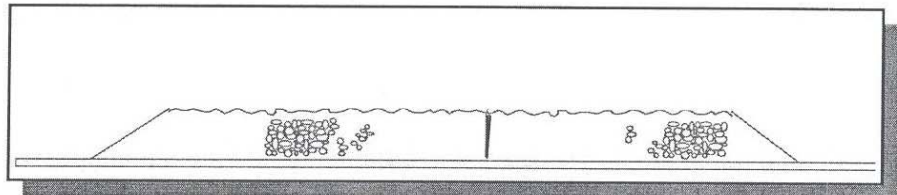
- **Approach for assessment / certification of TPS must address:**
 - Structurally critical failure modes
 - Debris critical failure modes
 - Inherent variability
 - Mechanical properties
 - Physical properties
 - Geometry induced defects
 - Verification/ validation of as-built hardware pedigree



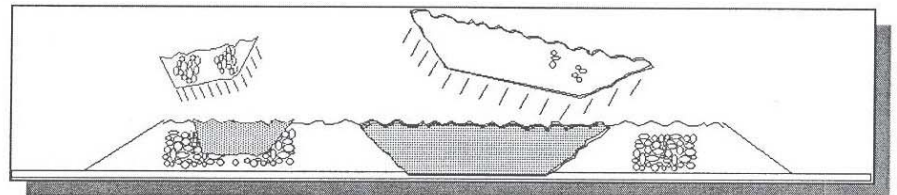
TPS Applications Identified for RTF Assessment / Certification



Bondline Delamination



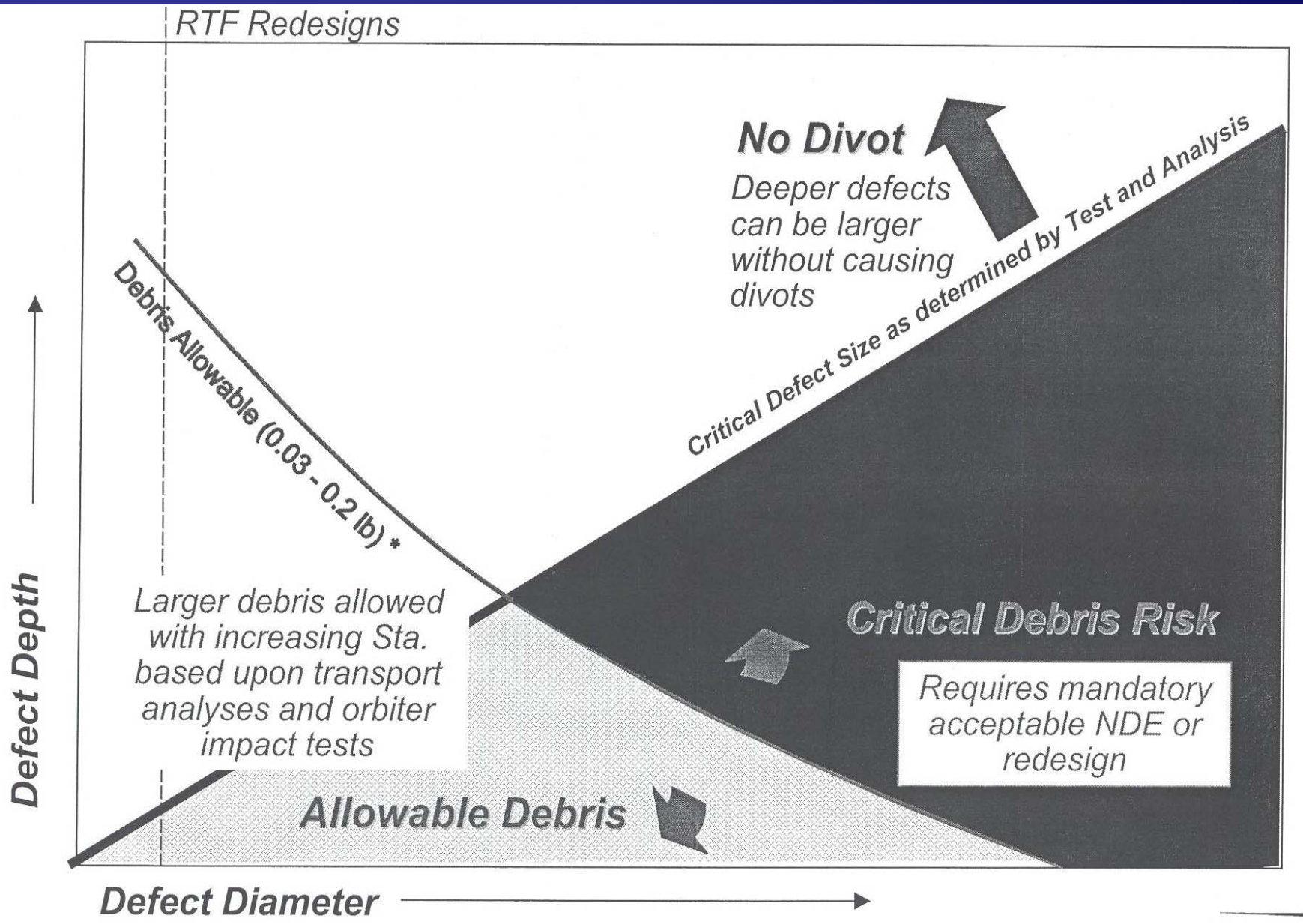
Outer Fiber Cracking



Cohesive -- Bond Adhesion Failure

Primary Debris Generation Concerns:

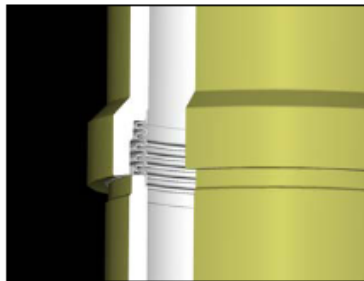
- Pressure due to vacuum at pre-existing defect
- Combined environment effects
- Combined failure modes



ET Major Design Changes

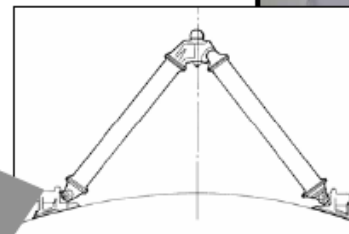


*Remove/ Replace
Longeron Closeouts*



*LO2 Feedline Bellows
TPS Drip Lip*

*Redesigned
Bipod Fitting*



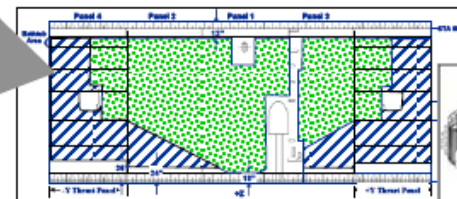
Bipod Strut Hardware



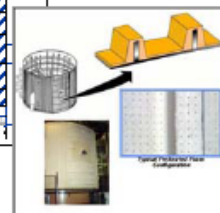
*Intertank / LH2 Tank
Flange Closeout
Enhancement*



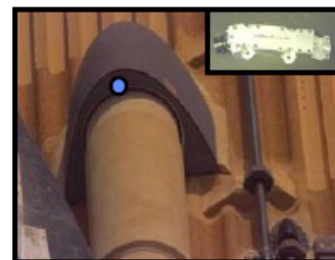
*Partial LH2 PAL Ramp
Replacement*



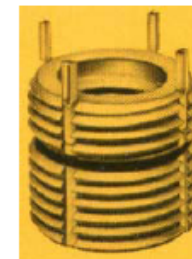
*Increase Area of Vented
Intertank TPS*



*ET/SRB Bolt
Catcher
Inserts*



*ET Camera in LO2
Feedline Fairing*

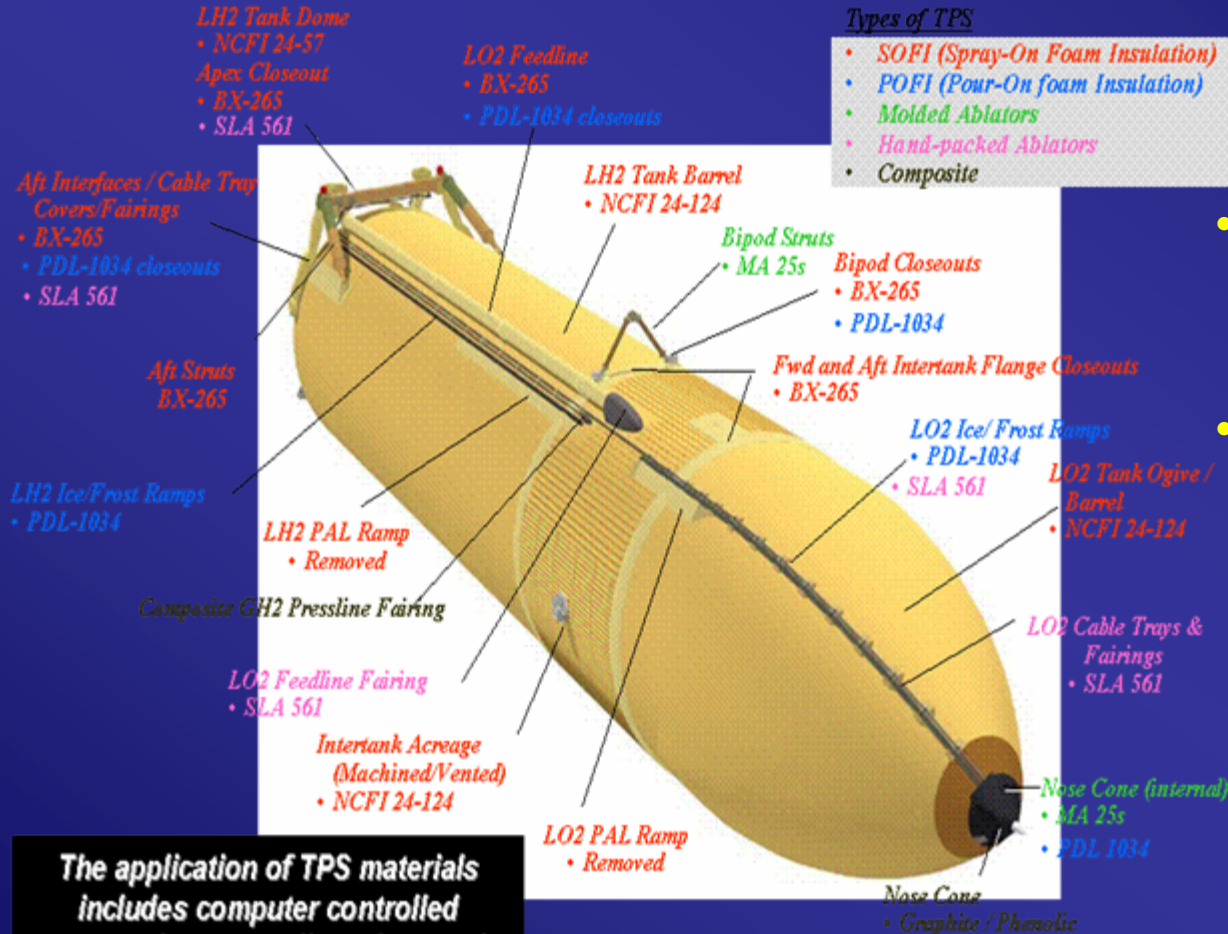


Return to Flight (RTF)

RTF concentrated on improved foam application processes to minimize defects (voids)

- Much tighter controls on workmanship
- More oversight and review
- Continuing practice
- Routine destructive evaluation of foam applied to near flight fixtures

Return to Flight (RTF)



- RTF included redesign of Bipods to eliminate the “ramp” and greatly reduce foam in the area
- Serious review of PAL ramp, which is the largest manually applied foam structure on the ET, showed no significant defects, no improvement in safety by removing and using new processes to reapply

Bipod Ramp



STS-107



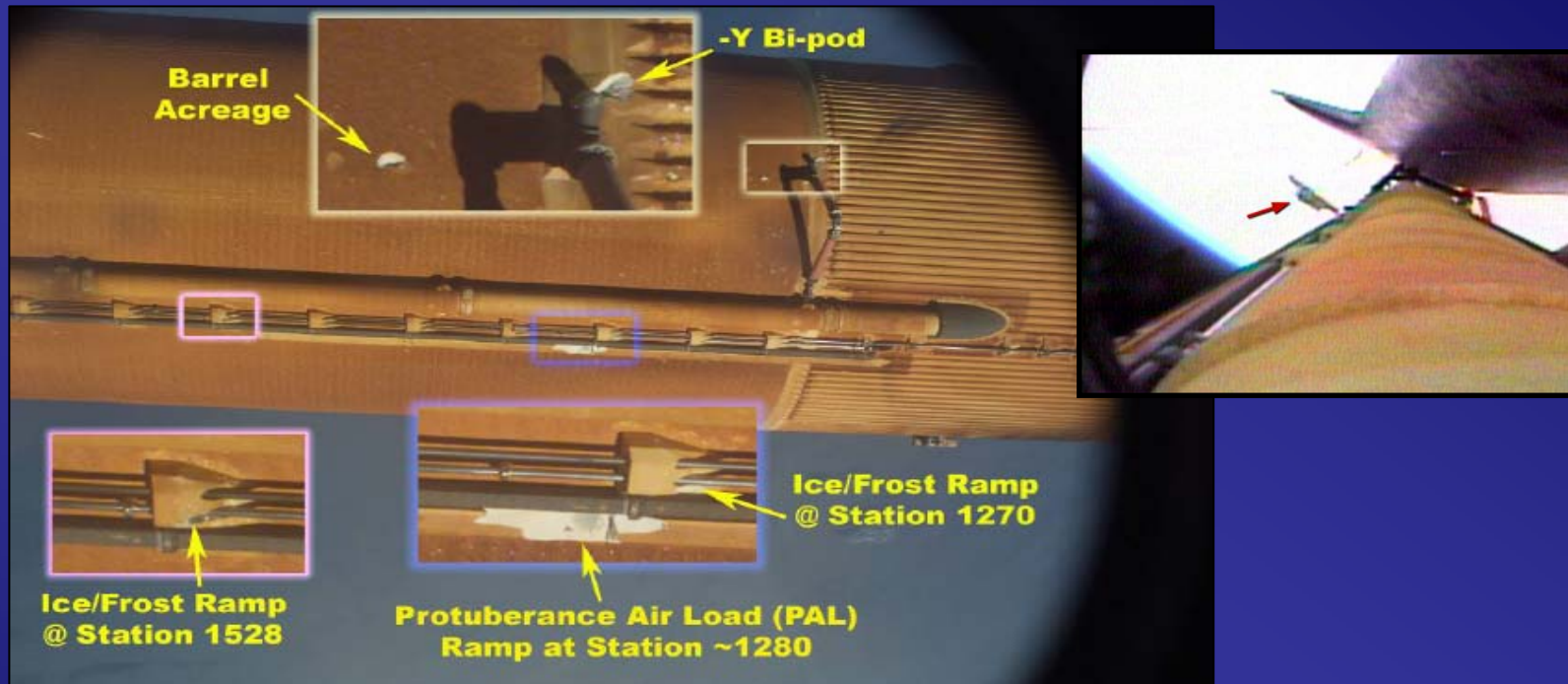
STS-114

Return to Flight (RTF)

Return to Flight was 2.5 years in the making

*It was noted in passing
that the defect/void divot debris generation theory
could not explain the STS-107 bipod loss.*

STS-114 RTF Results



- Major foam loss from Bipod wedge
- Major foam loss from Protuberance Air Load (PAL) ramp
- Significant foam losses around the Ice/Frost Ramps
- Near misses of Orbiter from all three areas could have been catastrophic

What Went Wrong?

How Could That Happen?



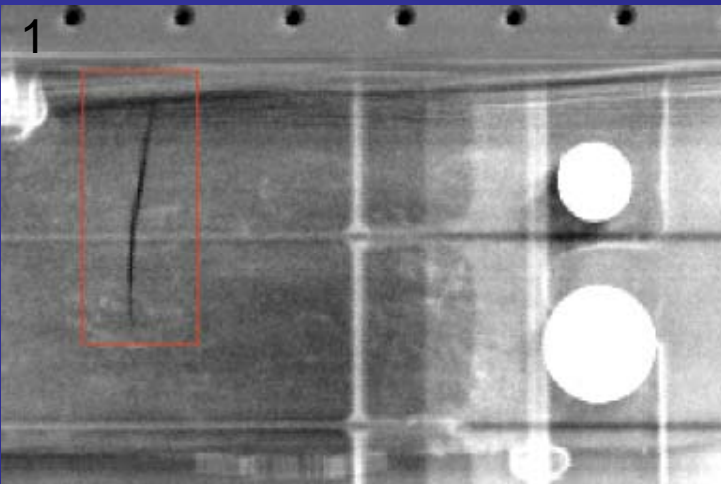
- Bipod “wedge” was lost because we introduced a new failure mechanism: *Cryopumping*
- Wires were not sealed which allowed air to liquefy and become the motive force to blow off significant foam

*Classic case of a new design
having an undesirable side effect!*

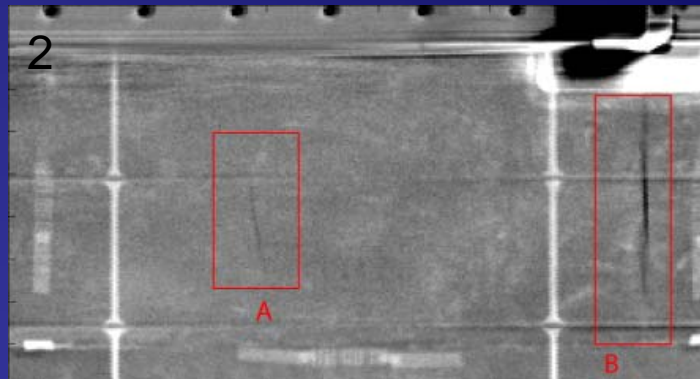
What About The Other Losses?

- ST-120 underwent 2 tanking cycles at KSC and then was shipped back to the factory
- Evaluation of the tank delayed until Michoud Assembly Facility (MAF) operations resumed following Hurricane Katrina
- Immediate observation: cracks in and under the PAL ramp and in and under the Ice Frost Ramp (IFR)

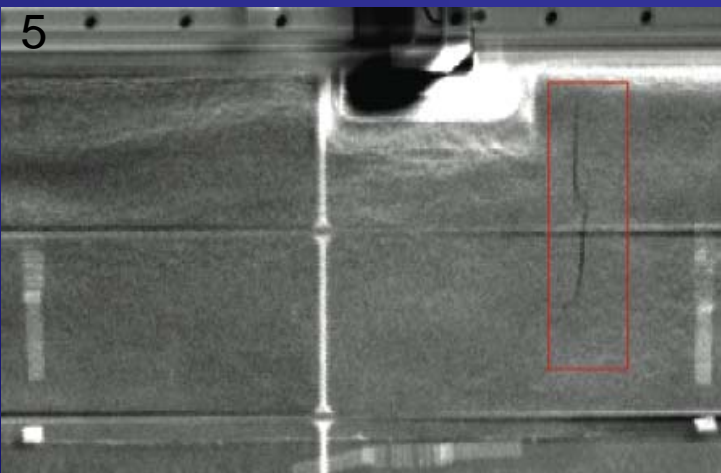
Not Seen in Previous Testing!



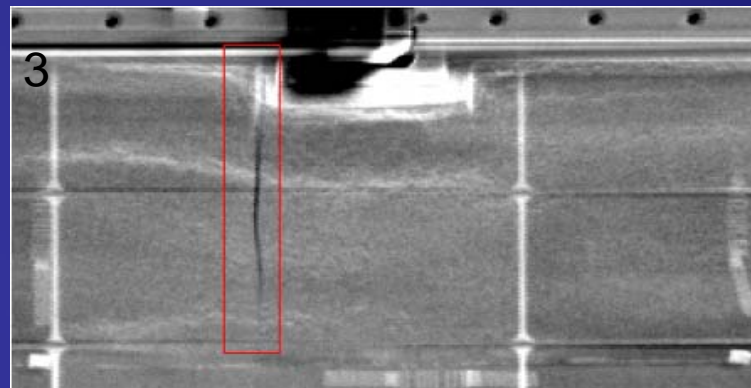
One of the first 2 cracks reported; crack that appears to be closed at the surface; found in zone 5 inspection



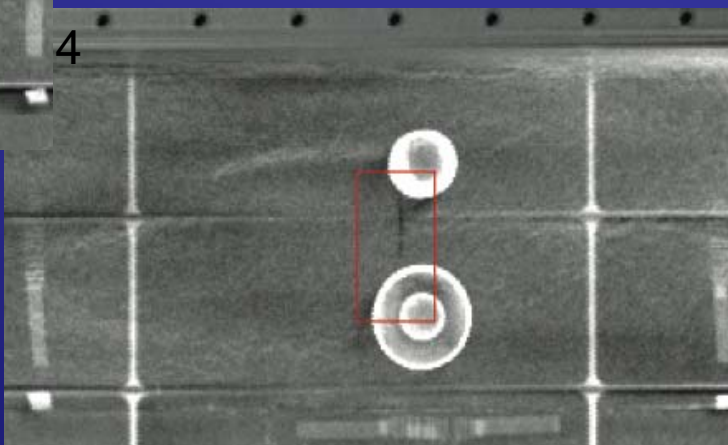
B is the second crack reported from visual inspection; A is crack found during backscatter inspection; found in Zone 6 inspection



Second crack detected during inspection on 11/3/05; found in zone 14



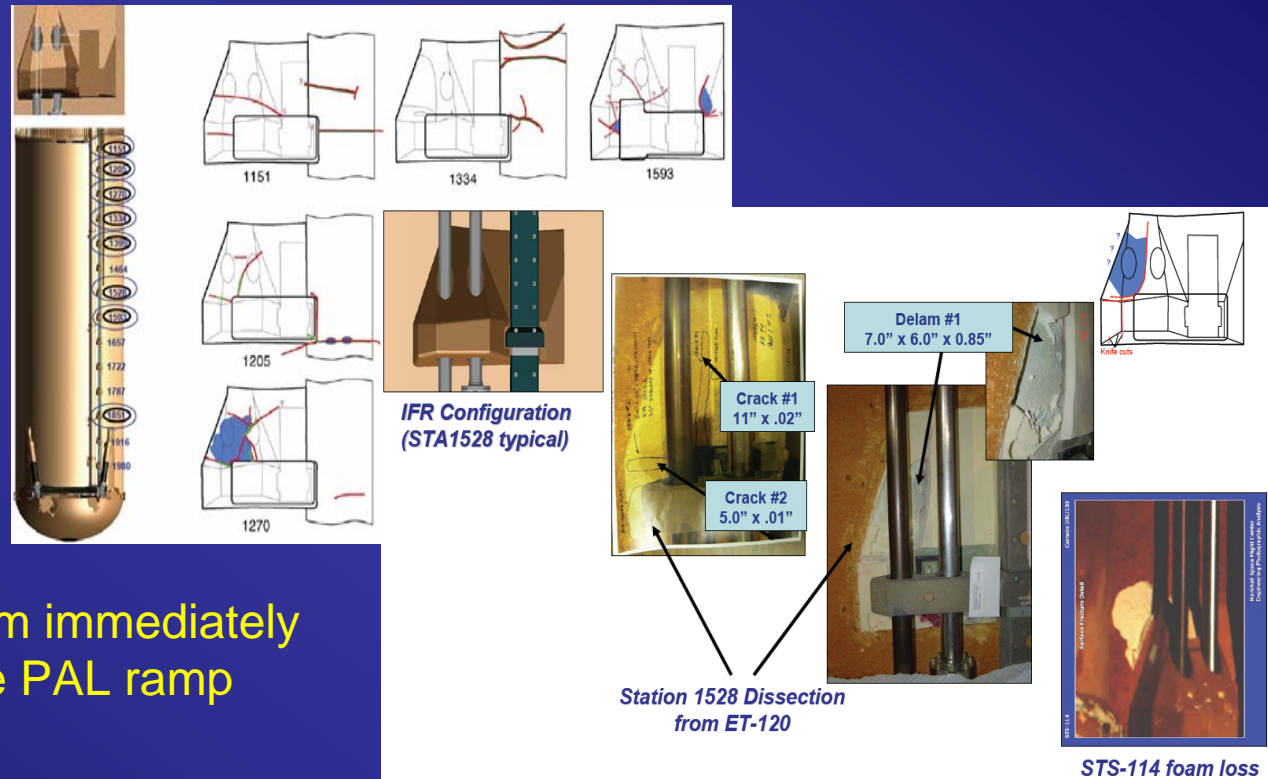
This is the 4th crack detected during a backscatter inspection; this is the first crack detected in BX250; found in zone 8



Crack detected during inspection on 11/3/05; appears to run between plugs and under or into the larger plug; found in zone 13

Relearning the Lesson

Turns out that the full size (test) article shows there is significant differences in thermal expansion for foam on foam application, which leads to cracks, primarily on the hydrogen tank



The Space Shuttle Program immediately directed the removal of the PAL ramp

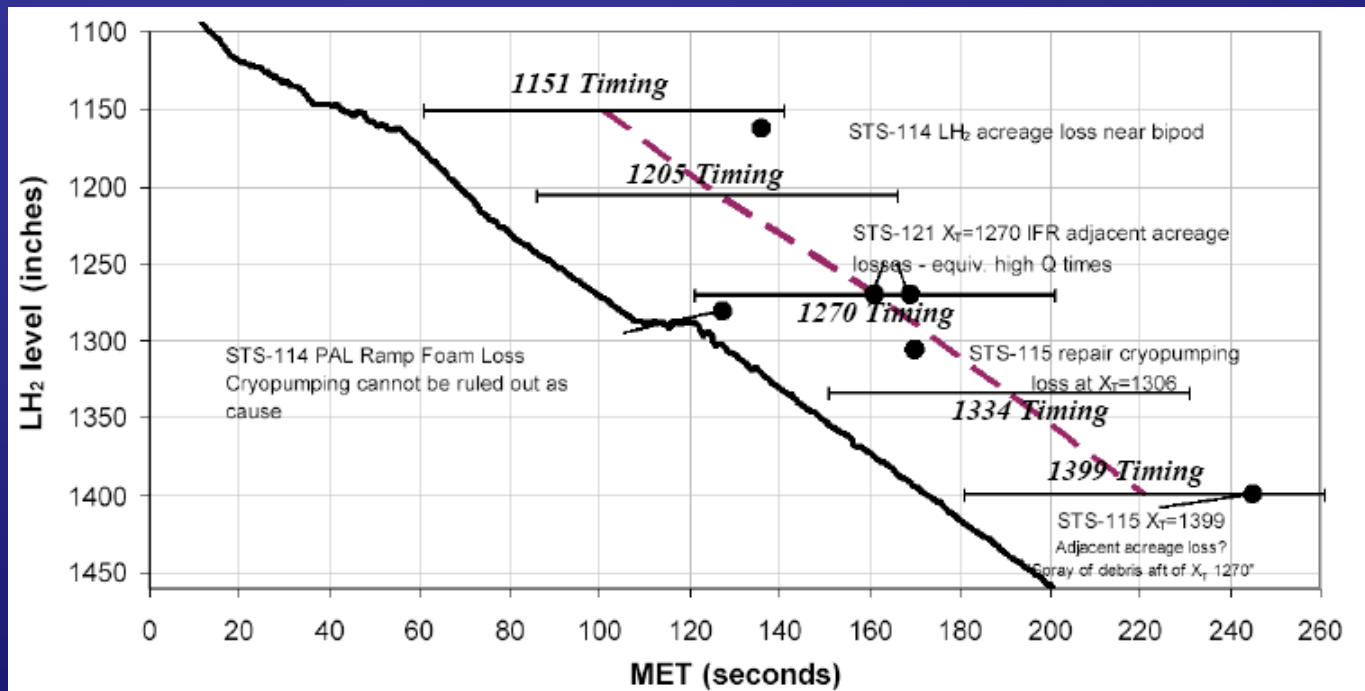
This caused a huge engineering recertification effort of the protuberances and their associated load capability!

But the time of loss during flight was not understood, so Probability Risk Assessment (PRA) analysis was based on the assumption that foam losses, as seen in ET separation photography (end state), were evenly dispersed during the ascent or assumed to all happen at the most critical times

This lead to extremely high probabilities of catastrophic failure prior to the second return to flight, STS-121

During STS-121, a very good image with new camera views showed a divot coming off the Ice Frost Ramp at a significant time

Detailed review of other video sources built up a record of when the Coefficient of Thermal Expansion (CTE) failure causes pieces to come off



Most losses will occur after the aero region where there is not motive force to cause damage, ergo, no hazard

ET Debris Table Sensitivity (Foam on Tile Void DeltaP Risk Assessment)

		Recorded in IDBR-01	Sensitivity Results	Sensitivity Results
	STS-121/115 Current ET Debris Table risk from foam on tile	STS-116 Current Debris Tables and Model Updates	STS-116 Adjusted for Flight History Release Rate	STS-116 Aerospace Physics Based Model
LH2 IFR Body	1/110	1/285	1/2,000*	1/1,250
LO2 IFR Body	1/70	1/65	1/1,000**	1/550 (combined)
IT IFR Body	1/185	1/200	1/3,000**	
LO2 Feedline Fairing	1/150	1/400	<1/10,000***	Not Computed
LO2 IT Flange	1/1,600	1/3,300	<1/10,000***	Not Computed

Impact of Model
Updates

Sensitivity of Debris
Table Conservatism

*Ratio of ~7:1 Observed to Predicted

**Ratio of ~15:1 Observed to Predicted

***Based on an assumed Ratio of >15:1

Debris Overview

	STS-114	STS-121/115	STS-116
PRA Models	<ul style="list-style-type: none"> -First Generation Model -Under-predicted risk -Only accounted for Void DeltaP and Cryopumping foam failures -Demonstrated the ability to calculate a risk index 	<ul style="list-style-type: none"> -Second Generation Model -Accounted for 3 additional foam failure modes observed on STS-114 -Ability to compare model prediction against flight performance -Foam model <u>believed</u> to over-predict the foam risk -Updated the ice on tile damage map 	<ul style="list-style-type: none"> -Third Generation Model -Significant model improvements (ie CFD, thermal, Popoff, release angle, grid geometry) -First Integrated foam risk -Foam model <u>shown</u> to over-predict the risk -Key foam model conservatisms identified and quantified
Vehicle Improvements	Bipod Closeout, Intertank Thrust Panel venting, new LH2 IT Flange, Fwd Bellows Heater, Bellows Drip Lip	PAL Ramp Removal, Bipod Heater Wire redesign, initial inspection of gap filler and putty repair	<ul style="list-style-type: none"> -Inspection, repair & replace gap fillers, blankets, putty repair and ceramic inserts -Liftoff debris mitigations
NSTS60559	-Multiple debris mass values	<ul style="list-style-type: none"> -Single debris risk assessment mass -Few exceedences 	-Few updates
NSTS08303	-Iceball formation could jeopardize a launch	<ul style="list-style-type: none"> -Iceball nomograph provided -Ice-to-foam bond strength testing completed 	<ul style="list-style-type: none"> -Allowable iceball mass as a function of X_t and Φ -Probabilistic Iceball results -Iceball combined environment testing
IDBR-01	<ul style="list-style-type: none"> -Difficult to rank relative risk -All critical debris risks had not been identified (ie PAL ramp) 	<ul style="list-style-type: none"> -Identified all critical debris sources and foam failure modes 	<ul style="list-style-type: none"> -Improved risk ranking and mitigation strategy tracking in SIRMA

Review of pre STS-107 imagery shows several flights where bipod losses occurred also had losses in foam adjacent to the bipod loss

Several more flights showed just losses in the adjacent acreage, which tends to confirm the Bipod foam loss of STS-107 was associated with CTE mismatch, not void defect divot

MORAL(S) of the Story:

1. You are never as smart as you think you are
2. If the hypothesis does not explain reality, the hypothesis is not right
3. Flight test is the only REAL test
4. Continually question your fundamental assumptions
5. Don't expect certainty

The Universal Abstract

“We have not succeeded in answering all of our problems. Indeed, we have not completely answered any of them. The answers we have found have only served to raise a whole new set of questions. In some ways, we feel as confused as ever, but we think we are confused on a much higher level about more important things.”